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ScienceDirect

Energy Procedia 122 (2017) 517–522

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

Climate-potential of earth-to-air heat exchangers

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Abstract

Amid several natural cooling sources that refer to thermal sinks (water, air, ground and night sky), a possible system is represented by the horizontal earth-to-air heat exchangers (EAHX). This technology, even if less diffused if compared to other geothermal systems, has been demonstrated to be effective alone and coupled with mechanical air-handling systems to reduce the energy consumption for both cooling and heating.
After a short review of existing EAHX simulation software, the paper will introduce a new simplified method to assess the potential of earth-to-air heat exchangers according to local soil composition and climate data.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: *Climate-potential; earth-to-air heat exchanger; passive cooling; HDD; CDH*

1. Introduction

In recent decades, the impact and the amount of consumed energy for cooling spaces has risen significantly. Furthermore, the diffusion of mechanical cooling systems in buildings has grown in both industrialised and emerging countries, reaching in some cases even +70% of the market income (2010-2015, emerging countries). Such an increase in energy consumption, especially in electricity, can be at least partially reduced by diffusing passive and hybrid solutions to treat and pre-treat inlet airflows in buildings.

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Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.300

1.1. EAHX systems

Among the four thermal sinks (air, water, ground, night sky), the ground can be used for both summer cooling, and winter pre-heating of a flow (air, water), thanks to its high thermal inertia that, at a given depth, produces an almost constant yearly temperature, which very closely corresponds to the average environmental yearly one. Several ground-cooling techniques are known and can be classified, according to [1], in: buried or semi-buried buildings, horizontal earth-to-water heat exchangers (EWHE), earth-to-air heat exchangers (EAHX), and borehole heat exchangers (BHE). Other possible classifications are reported in [2-4], where buried and semi-buried buildings are classified as indirect dissipative passive systems, while horizontal tubes using both air and water (single tube, fields or pond) are classified as isolated dissipative passive systems.

2. EAHX calculation tools

Several tools allow us to design and optimize an EAHX system. One of these is the software GAEA, developed by the Software Laboratory for Low Energy and Solar, Siegen University [5]. This software is user-friendly and allows us to optimize an EAHX in building design – see also the parametric analysis reported in [4]. A comparison between GAEA-designed and monitored data is reported in [6]. Furthermore, more precise analyses can be performed by using dynamic energy simulation software. In TRNSYS it is possible to use the devoted Type 31 or, in the TESS libraries v.17, the GHP (Geothermal Heat Pump) components. Devoted models were reported in [7]. In EnergyPlus, EAHX can be simulated using the method described by [8] and further validated in [9]. Computational fluid dynamic analyses were also performed, as reported for example in [9] using Fluent.

Geothermal cooling systems can be applied in the majority of climates, with the exception of very hot tropical soils – too high ground temperature –, and very cold locations – low cooling demand [1]. When the soil surface temperature is too high, it is possible to adopt specific techniques (e.g. water evaporation) to reduce it in order to increase the applicability of such cooling techniques [10], while in [11] the effect of different surface materials on the performance of EAHX was analysed. Furthermore, the applicability of EAHX in three Italian climates was studied in [12], while their usage in Mediterranean areas for NZEB was analysed in [13] using simulations. Of the few monitored case studies in European climates, [6,14,15] is noteworthy.

This paper aims to introduce a climate-related tool to estimate the local potential of EAHX in preliminary design phases (e.g. building programming) by considering the “potential” effect of this system in comparison to the local climatic heating and cooling demand. Related studies on the climate-potential of other passive cooling dissipative techniques are reported in [16] for natural ventilation, and in [17] for direct evaporative cooling.

3. EAHX estimation tool

In this paper, a new methodology is presented to assess the climate-related potential of EAHX in space cooling and winter pre-heating. Acting as a sensible heat exchanger, the EAHX potential relates to the difference in temperature between the inlet air and the ground, which acts as a thermal sink, and the efficiency of the thermal exchange. The proposed method aims at predicting the outlet temperature (ϑ_{out}) of an airflow by considering on an hourly basis these three fundamental parameters: the environmental temperature (θ_{in}), the ground temperature at a given depth ($\vartheta_{soil,h}$), and the EAHX effectiveness (ε) – see Sec. 3.3 – according to the following expression:

$$\vartheta_{out} = \vartheta_{in} - \varepsilon * (\vartheta_{in} - \vartheta_{ground,h}) \qquad [°C] \qquad (1)$$

Furthermore, the calculated outlet temperature will be used to analyse the climate-related applicability of EAHX considering local heating and cooling climate-related energy demand – see Sec. 4.

3.1. Environmental temperature

The hourly variation of the local environmental temperature can be gathered from local meteorological stations, or by using typical meteorological years (TMY) and other local climate data. Several databases are available, such as the weather database of EnergyPlus, which gathers data from several sources, the TRNSYS database, the software Meteonorm, or, in national cases, specific sources –e.g. for Italy the recent database developed by the CTI– and standards, such as the UNI 10349:2016 reporting monthly average values. The choice of a specific TMY source can significantly influence the results of simulations, as was demonstrated in [18,19]. For the aims of this paper, TMY used in Sec. 4 are based on the EnergyPlus database.

3.2. Ground temperature

The ground temperature at a given depth is a function of two principal boundary conditions: the yearly cyclical behaviour of the soil surface temperature and the constant yearly temperature of the ground at a consistent depth (around 100m) [20]. The constant ground temperature can be roughly approximated in a specific location by measuring the temperature of the water in a sink or by adding 1-1.5°C to the average yearly environmental temperature [21]. On the other hand, the soil surface temperature is harder to estimate due to the various factors that influence it directly (e.g. solar radiation, soil humidity, the presence of vegetation, soil colour, soil thermal properties,…). Nevertheless, diurnal variations are less important as regards the use of the ground as a thermal sink since they principally influence the first centimetres of depth [1, 20]. For this reason, the surface temperature of the soil can be defined for ground cooling as a yearly fluctuation around its average yearly value [1]. Several models were reported for estimating this temperature [1, 22].

In order to calculate the ground temperature in a location at a given depth, which is the required parameter to estimate the EAHX potential, it is possible to use the simplified algorithm developed by Hadvig [4, 23]:

$$\vartheta_{groud,h} = \vartheta_{sf,av.} + A_s \cdot \exp\left(-h\sqrt{\frac{\pi}{\alpha \cdot t_0}}\right) \cdot \cos\left(\frac{2\pi}{t_0} \cdot (t - t_{\max}) - h\sqrt{\frac{\pi}{\alpha \cdot t_0}}\right) \quad [°C] \tag{2}$$

Where: h is the depth of the ground where the temperature is calculated [m]; $\vartheta_{sf,av.}$ is the annual mean temperature of the soil surface [°C]; A_s is the semi-amplitude of the annual soil surface temperature variation [°C]; α is the ground diffusivity [m^2/s] calculated as follows: $\alpha = \lambda/\rho c$, where λ is the soil thermal conductivity [W/mK], ρ is the soil density [kg/m^3], and c is the specific heat of the soil [J/kgK]- see table 1; t_0 is the yearly duration [s]; t is the moment of the year in where the temperature is calculated [s]; t_{max} is phase shift constant assumed as the maximum environmental air temperature moment [s].

Table 1. Principal soil thermal characteristics [4].

Terrain types	ρ kg/m^3]	λ [W/mK]	c [J/kgK]	α [m^2/s]
Wet clay	1800	1.49	1340	$6.18 * 10^{-7}$
Dry clay	1650	2.3	2850	$4.89 * 10^{-7}$
Limestone	1670	0.71	2230	$1.91 * 10^{-7}$
Sand	1520	1.24	1650	$6.94 * 10^{-7}$

3.3. EAHX effectiveness

The effectiveness of an EAHX can be calculated according to the Scott, Parson and Koehler's formula [6,14,20] reported here below:

$$\varepsilon = (\vartheta_{in} - \vartheta_{out}) / (\vartheta_{in} - \vartheta_{ground,h}) \quad [-] \tag{3}$$

Where: ϑ_{in}, ϑ_{out}, $\vartheta_{ground,h}$ are respectively the inlet, outlet and ground temperatures.

This parameter can be used to compare EAHX systems and their effectiveness both in winter and in summer as was underlined in literature [6, 15]. The average ε in these quoted monitoring analyses was calculated to be around 0.6-0.7, while a classification of frequencies in different ε domains shows that the most numerous class is the one ranging from 0.8 and 0.9.

4. EAHX climate-potential tool and sample applications

In this section, a method to analyse the climate-potential of EAHX in a given location is introduced by considering the seasonal distribution of the hourly "virtual" outlet temperatures of a treated airflow (ϑout). The "virtual" outlet temperatures are calculated according to the methodology introduced in Sec. 3 using the hourly distribution of environmental air temperature of the local TMY (see Sec. 3.1). These values are used to define an EAHX adapted version of the recent indicator "residual" cooling and heating demand introduced in [16, 17].

The climate potential of the system is analysed, in fact, based on its ability to reduce, on a treated airflow, the climate-related "virtual" energy demand for both cooling and heating. These two last values are climatically defined using the consolidated indexes heating degree-days (HDD), whose calculation was performed, according to the UNI EN ISO 15927-6:2008, and cooling degree hours (CDH) using the following expressions:

$$HDD_{set.temp} = \left[\sum_{h=1}^{n} \Delta\vartheta_h\left(set_{temp.}\right)\right] / 24 \tag{4}$$

Where if $\vartheta_h < set_{temp.}$ then $\Delta\vartheta_h(set_{temp}) = (set_{temp} - \vartheta_h)$ else $\Delta\vartheta_h(set_{temp}) = 0$. n represents the hours in the extended winter season (Oct-Apr) – see also [24].

$$CDH_{set.temp} = \sum_{h=1}^{n} \Delta\vartheta_h\left(set_{temp.}\right) \tag{5}$$

Where if $\vartheta_h > set_{temp}$ then $\Delta\vartheta_h(set_{temp}) = (\vartheta_h - set_{temp})$ else $\Delta\vartheta_h(set_{temp}) = 0$. Extended summer season (May-Oct).

The base temperatures ($set_{temp.}$) are here assumed to be 20°C for winter, see also [24], and 22°C for summer, see the lower comfort value of the Givoni-Milne chart [25], considering the effect of the EAHX on the internal air. It is possible to define the "virtual" climate-related residual cooling and heating demand with the following expressions:

$$HDD_{20,res-EAHX} = \left[\sum_{h=1}^{n}\left(20 - \vartheta_{out}\right)\right] / 24 \quad \text{[only positive values]} \tag{6}$$

$$CDH_{22,res-EAHX} = \sum_{h=1}^{n}\left(\vartheta_{out} - 22\right) \quad \text{[only positive values]} \tag{7}$$

The ratio between the climate original "virtual" demand and the residual one can be assumed as a parameter to define the EAHX climate-potential in a specific location, if we know local temperature variations and the ground composition.

4.1. Sample applications

Six sample locations were chosen to represent different typical Central and southern European climates according to the Köppen-Geiger climate classification as reported in the EnergyPlus *epw file: Paris (Cfb); Geneva (Cfb); Turin (Dfb); Rome (Cfa); Lecce (Csa); and Athens (Cfa). The soil typology is fixed as wet clay [12], assuming as reference the relative values from table 1. The calculated ground temperatures at different depths are reported in Figure 1 according to equation (2) for the three Italian locations.

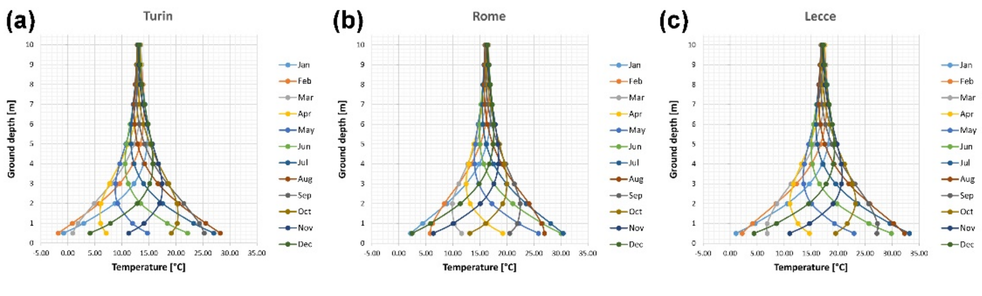

Fig. 1. Calculated ground temperature profiles considering different depths for (a) Turin; (b) Rome; (c) Lecce.

The yearly variation of the "virtual" outlet temperatures on an hourly basis is reported for the six considered locations in Figure 2, assuming a reference depth of 3 meters.

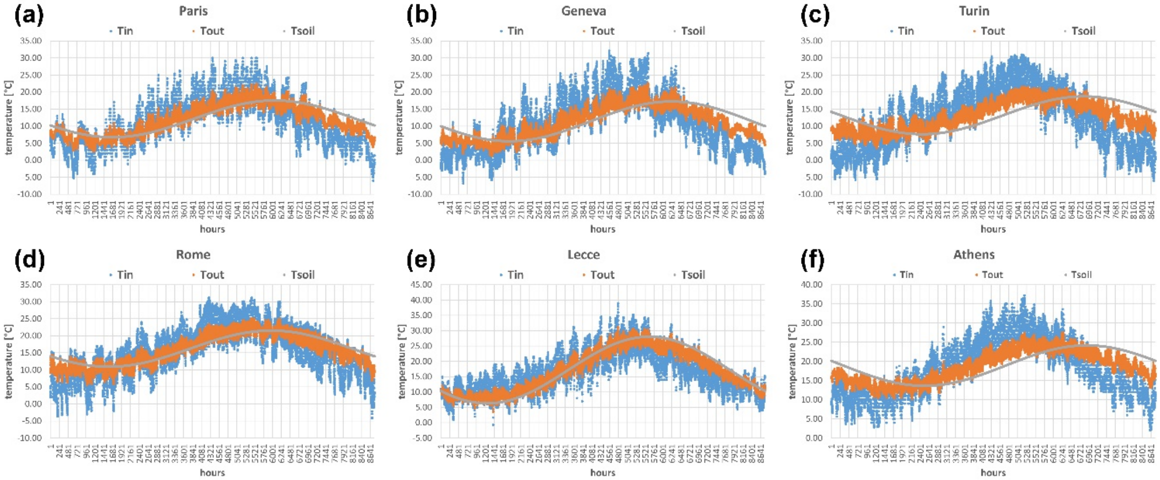

Fig. 2. Yearly variation of the external, ground (3 m depth) and "virtual" EAHX-outlet temperatures for (a) Paris; (b) Geneva; (c) Turin; (d) Rome; (e) Lecce; (f) Athens.

Furthermore, the calculated HDD and CDH and the residual indexes are reported in Table 2. According to these results, the "virtual" potential of EAHX in covering the climate-related "virtual" demand is very high in summer showing that this cooling technique can be used as a primary cooling source of an airflow in several conditions. From the heating point of view, an evident action of pre-heating is underlined ranging, on a seasonal basis (Oct-Apr), from 17% to 46%. On the other hand, if the optimum conditions are chosen between external and treated air ($HDD_{20,res\text{-}EAHX\ OP.}$; $CDH_{22,res\text{-}EAHX\ op.}$), simulating a control system, the climate-related potential of the EAHX system substantially increases thanks to the reduction of the negative effect in middle-seasons ranging from 20% to 49%.

Table 2. HDD (Oct-Apr) and CDD (May-Oct) in the considered locations.

Locations	HDD_{20}	$HDD_{20,res\text{-}EAHX}$	$HDD_{20,res\text{-}EAHX\ OP}$	CDH_{22}	$CDH_{22,res\text{-}EAHX}$	$CDH_{22,res\text{-}EAHX\ OP}$
Paris	2808	2328	2240	1514	2	2
Geneva	3072	2505	2394	2304	2	2
Turin	2816	2013	1896	3665	0	0
Rome	1897	1462	1383	5129	844	844
Lecce	1675	1176	1097	7289	1924	1833
Athens	1506	810	768	12808	3746	3396

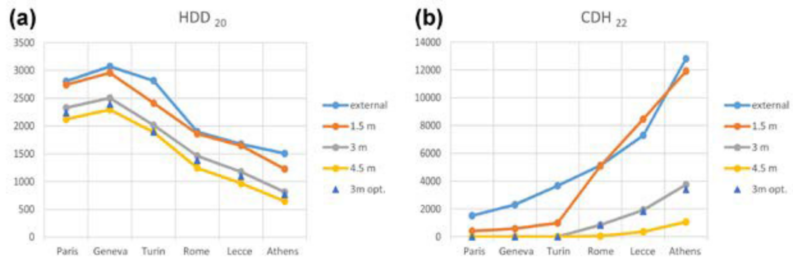

Fig. 3. Climate-related HDD (a) and CDH (b) according to different depths for the six chosen locations.

The influence of different depths on the HDD and CDH performances is seasonally analysed in figure 3. As shown in graph (b), at the lowest depth (1.5 m) the continuous use of the system may affect its potential because diurnal-nocturnal variations in the external temperature are lost. In summer, the "virtual" control of the system (at 3 m in depth) has less impact on the results than it does in the winter season (see Fig. 3a).

5. Conclusions

Present tools and methods which are able to calculate the performance of an EAHX require, in order to be used, a precise definition of the system and, for several of them, of the coupled building. On the other hand, the methodology here introduced will allow us to obtain a preliminary idea of the climate-related applicability of an EAHX before the definition of the building and the complete system itself, introducing the possibility to pre-define, at a low cost and quickly, the potential of such a technique in a location. This instrument can be used easily by professionals to pre-verify the climatic potential of this technological solution in the building programming design phase in order to introduce as soon as possible environmental issues in the design process. The samples proposed in Sec. 4 show the applicability of the introduced methodology in different climate contexts. Nevertheless, the author notes that other factors may also influence the EAHX applicability such as building insulation standard, internal and solar gains. Further researches are under development to improve this methodology by using large monitored databases, comparisons with dynamic energy simulations, considerations on the heat exchange along the tube [6], and a large climate database.

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